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CBR-Beta Design Procedure for Aggregate-Surfaced Airfield Pavements

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Abstract

During contingency operations, aircraft are required to land, taxi, and take off on unpaved surfaces. Limited time available to establish airfield operations may not allow for the construction of paved surfaces. The original flexible pavement design procedure of paved surfaces, which is based on the California Bearing Ratio (CBR) and the α-factor (Alpha-factor), was also extended and applied to the design and evaluation of aggregate-surfaced pavements. With the reformulation of the CBR-Alpha for the design of flexible pavements, efforts were also directed in defining a new equation for the design of aggregate-surfaced airfields. This report presents the development of a new CBR-Beta procedure for the design and evaluation of aggregate-surfaced airfields. Data from previous studies conducted on aggregate-surfaced, full-scale test sections were used for this purpose. The new performance curve proposed in this report for aggregate-surfaced airfields has the same equation format as that proposed and accepted for flexible pavements.

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Preface

The study was conducted as part of research centered on the review of the design procedure for flexible pavements. The study was sponsored by the US Air Force.

The work was performed by the Airfields and Pavements Branch (GM-A) of the Engineering Systems and Materials Division (GM), US Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Dr. Gary L. Anderton was Chief, CEERD-GM-A; Dr. Larry N. Lynch was Chief, CEERD-GM. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Dr. David W. Pittman.

COL Jeffrey R. Eckstein was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
pounds (mass) per square yard	0.542492	kilograms per square meter
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters

1 Introduction

During contingency operations, aircraft may be required to land, taxi, and take off on unpaved surfaces. Limited time available to establish airfield operations may not allow for the construction of paved surfaces. The original flexible pavement design procedure for airfield surfaces, which is based on the California Bearing Ratio (CBR) and the α-factor (Alpha-factor), was extended and applied to the design and evaluation of aggregate-surfaced unpaved surfaces. With the reformulation of the CBR-Alpha for the design of flexible pavements, efforts were also directed at defining a new equation for the design of aggregate-surfaced airfield pavements.

The current flexible pavement design procedure used by Department of Defense (DoD) is based on the CBR and the factor β (Beta). The CBR value is used as an index to quantify the subgrade shear strength. The design procedure determines the pavement total thickness required to prevent the subgrade from shearing when subjected to aircraft loads. The procedure developed for aggregate-surfaced pavements is based on the same principle of protecting the subgrade from shearing by providing sufficient cover of aggregate material with a minimum CBR value.

This report presents the development of the procedure for the design and evaluation of aggregate-surfaced airfields. Data compiled from previous studies and full-scale testing were used for this purpose. The new performance curve proposed in this report for aggregate-surfaced pavements has the same format and equation as that newly developed and accepted for flexible pavements.

1.1 Background

The use of aggregate-surfaced (or unsurfaced) pavements for contingency operations has been fundamental to the successful completion of military mission-critical operations in recent military scenarios. The current flexible pavement design criteria require corrections that account for the different performance and degradation of aggregate-surfaced pavements. The performance of aggregate-surfaced pavements is greatly affected by climate conditions and the presence of water, especially in frost areas and frost-susceptible soils. Moreover, additional performance indicators may be used to better represent the aggregate-surfaced pavement and its response when subjected to traffic. Material characteristics, such as gradation of the gravel-sand particles and plasticity properties of the fine fraction, also have a decisive impact on the stability of aggregate-surfaced pavements under repetitive loads (Chou 1989).

The need for reformulating the design procedure for aggregate-surfaced pavements evolved from the newly implemented design procedure for flexible pavements. With the objective of maintaining consistency between the two design procedures, the US Army Engineer Research and Development Center (ERDC) research team evaluated the possibility of redefining the design procedure for aggregate–surfaced airfields, using the same fundamental concepts employed in the newly developed design procedure for flexible pavements.

The US Army CBR procedure for flexible pavement design was originally developed in the 1940s by using the California empirical design curves for highway pavements. The design equation was subsequently modified to account for heavy multi-wheel aircraft, such as the C-5A and B-747, by introducing the correction factor α. The factor α depended on the number of coverages and number of wheels on the main landing gear employed to calculate the equivalent single-wheel load (ESWL) (WES 1971).

An analysis of the stress-based response model and CBR was started in 2000, and it further questioned the then-current CBR equation for the design of flexible pavements. Such analytical conclusions convinced the US Army ERDC research team to investigate the design issue by reformulating the CBR procedure. In 2009, a new design procedure was proposed and ultimately adopted. The new procedure was developed on the Fröhlich's theory centered on the stress distribution in the soil mass (Gonzalez, Barker, and Bianchini 2012). The reformulation of the CBR equation in terms of stress concentration factor permitted the development of design criteria based on the β parameter, which represented the ratio of the applied vertical stress to the allowable vertical stress.

The current design equation for aggregate-surfaced airfields is based on the same elements of the CBR-Alpha equation for flexible pavement design, which includes the ESWL and the CBR of the subgrade. The work by Hammitt (1970) resulted in Equation 1 for the design of aggregate-surfaced pavements, including roads and airfields:

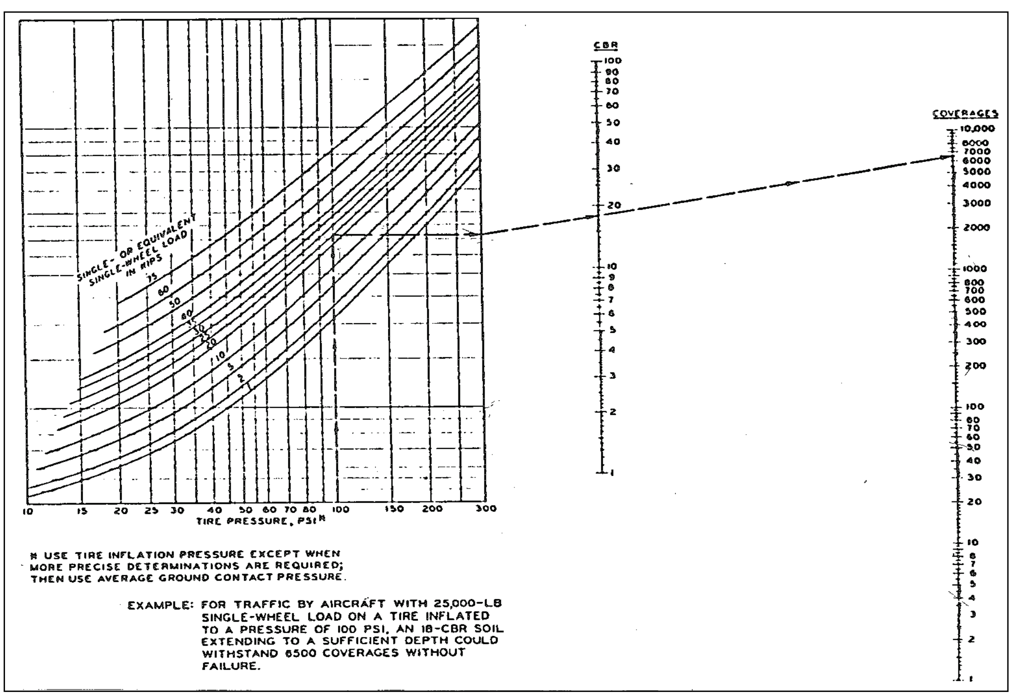
$$t = [0.176 \log(Cov) + 0.120] \sqrt{\frac{P}{8.1CBR} - \frac{A}{\pi}} \tag{1}$$

where:

t = aggregate layer thickness (in.)
Cov = number of aircraft coverages
P = single or equivalent single-wheel load (lb)
CBR = subgrade CBR value
A = tire contact area (in.^{2})

In his review, Chou (1989) pointed out that Equation 1 was developed on the basis of full-scale testing with a limited range of layers and material characteristics. The surface cover material CBR values varied between 7 and 17, the maximum number of coverages was 700, and only a limited number of pavement test items had coverage levels above 100. The failure criteria were based on permanent deformation or rutting in combination with elastic deflections. Specifically, failure was defined as a surface rut depth of 3 in. or greater or elastic surface deflection greater than 1.5 in. Additional studies led to the replacement and update of Equation 1. Ahlvin and Hammitt (1975) provided the new design Equation 2 and the nomograph (Figure 1) for computing the required aggregate layer thickness and CBR.

Figure 1. Nomograph to determine the required CBR of the aggregate surface layer (Ahlvin and Hammitt 1975).



$$t = [0.128 \log(Cov) + 0.087]\sqrt{\frac{P}{8.1CBR} - \frac{A}{\pi}} \tag{2}$$

Multiple past research efforts proposed other design equations for aggregate-surfaced pavements in response to specific agencies' needs. In 1978, the US Department of Agriculture, Forest Service sponsored the development of another equation to define the aggregate-surfaced road performance in relation to surface rutting. Barber, Odom, and Patrick (1978) proposed the following deterministic equation (Equation 3) to predict road rutting deterioration. Equation 3 was developed from full-scale test sections having CBR values between 8 and 17:

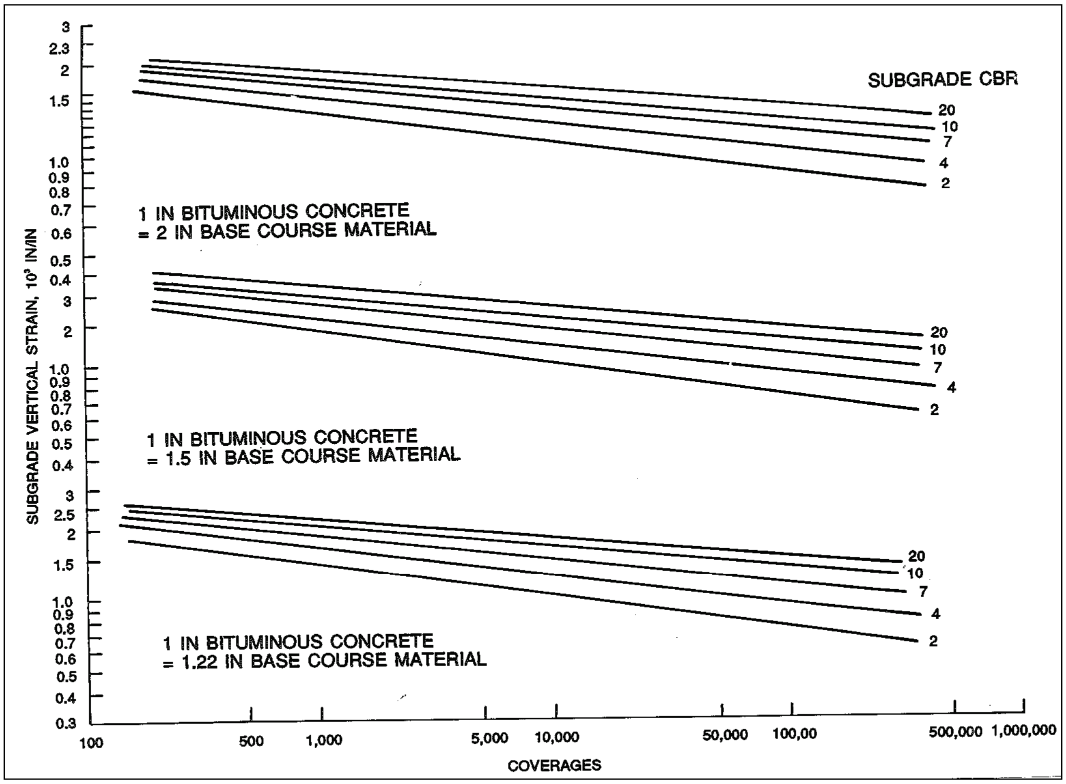
$$RD = 0.1741 \frac{P_k^{0.4707} t_p^{0.5695} R^{0.2476}}{(\log t)^{2.002} C_1^{0.9335} C_2^{0.2848}} \tag{3}$$

where:

RD = rut depth (in.)
P_k = equivalent single-wheel load (kips)
t_p = tire pressure (psi)
t = thickness of the gravel layer (in.)
C_1 = CBR of the gravel layer
C_2 = CBR of the natural subgrade

With the dissemination of the layered elastic methodologies for design, Chou (1989) proposed a layered elastic procedure for the design of aggregate-surfaced pavements for track, tracked, and aircraft loadings. Deriving it from the CBR-Alpha equation for flexible pavement design, Chou's proposed layered elastic procedure was based on the principle that the asphalt surface layer can be converted into an equivalent base course layer by using an equivalency factor. In this effort, Chou (1989) also reformulated the failure criteria for gravel pavements as a function of the vertical strain at the subgrade level, the number of coverages to failure, the subgrade CBR, and the equivalency factor between asphalt and base course materials. Figure 2 summarizes Chou's failure criteria for aggregate-surfaced roads and airfields.

Figure 2. Failure criteria for aggregate-surfaced pavements for roads and airfields (Chou 1989).



1.2 Objective

The objective of this research was to reformulate the CBR-Alpha procedure for the design of aggregate-surfaced airfields. The goal was to redefine the design procedure of aggregate-surfaced airfields using the CBR-Beta approach already implemented for the design of asphalt-surfaced pavements. The final objective was to provide consistency in the design of asphalt-surfaced and aggregate-surfaced pavements, since both structures are represented by a layered system and the design principle for either structure is to prevent the subgrade from shearing.

The reformulation of the design procedure for flexible pavements is based on Fröhlich's theory of stresses. This theory offered the opportunity to revise the design equation for aggregate-surfaced pavements and applied a more rational pavement response model. The database utilized for this purpose included data from full-scale tests conducted in the 1960s and 1970s as well as data from recent tests conducted at ERDC on mat-surfaced test sections.

1.3 Report content

Chapter 2 explains Fröhlich's theory of stress distribution, the CBR-Beta reformulation, and the databases used for developing and validating the CBR-Beta procedure. Chapter 3 contains the comparison between the CBR-Alpha and the CBR-Beta procedures. Chapter 4 closes the report with conclusions and recommendations about the implementation of the new CBR-Beta procedure for the design and evaluation of aggregate- surfaced pavements.

2 Reformulation of the CBR-Alpha Equation

The original curves for designing aggregate-surfaced pavements were derived from those empirically developed from the California method, which utilized Boussinesq's theory of stress distribution in a homogenous half-space. The reformulation of the CBR-Alpha design procedure for paved flexible pavement using Fröhlich's theory of stress distribution in the half-space provided a new opportunity to redefine the existing design procedure of aggregate-surfaced pavements. The purely empirical nature of the design methodology is replaced with a more rational mechanistic-empirical approach.

2.1 Fröhlich's theory on stress distribution

Fröhlich concluded that the theory of elasticity was not totally satisfactory in representing laboratory stress measurements. Fröhlich introduced the concentration factor n in order to account for the Young modulus variability with depth, noting that in soil mass the Young modulus increases with depth (Jumikis 1969). Moreover, Fröhlich's theory was based on the principle of linear stress distribution and assumed an anisotropic semi-infinite medium, changing Boussinesq's assumption of isotropy.

Fröhlich's approach was based on the assumptions that the stress σ_R at point Q in the medium in the radial direction connecting the point of load application to Q was a major principal stress and that the tangent stress was equal to zero (Veverka 1973). The formulas expressing the radial and vertical stresses at the generic point Q located at depth z are

$$\sigma_R = \frac{nP}{2\pi R^2}(cos\theta)^{n-2} \tag{4}$$

$$\sigma_z = \frac{nP}{2\pi R^2}(cos\theta)^{n} \tag{5}$$

where:

θ = angle formed by the vertical line through the applied point load and the line connecting the load application point to point Q in the medium

R = radial distance between Q and the point of load application
n = concentration factor
P = applied load

For vertical stress at depth z along the centerline of a uniformly distributed circular load, Equation 5 becomes (Ullidtz 1998)

$$\sigma_z = \sigma_0 \left[1 - \frac{1}{\left(\sqrt{1 + \left(\frac{r}{z} \right)^2} \right)^n} \right] \tag{6}$$

where:

r = radius of the load
z = depth to the location of the computed stress
n = concentration factor
σ_o = applied stress over the loaded area

When the concentration factor n is equal to 3, the above equations correspond to those produced by the Boussinesq's theory for an elastic isotropic body. Based on Fröhlich's theory, the concentration factor magnitude is related to the nature of the soil and the size of the loaded area. The concentration factor equal to 3 is possible only in an elastic, isotropic medium with a constant Young's modulus, a medium that follows Hooke's law. A stress concentration factor equal to 4 characterizes a medium with Young's modulus increasing linearly with depth z through the equation (Jumikis 1964)

$$E = cz \tag{7}$$

where:

c = arbitrary constant

2.2 The database

The database utilized in the reformulation of the design procedure for aggregate-surfaced pavements included data derived from full-scale tests performed in previous research efforts (e.g., Ladd 1970; Hammitt 1970).

The data provided by Ladd (1970) were collected from full-scale pavement testing that had the objective of reviewing the soil strength criteria for the operation of jet fighter aircraft on aggregate-surfaced airfields. The full-scale test included two test sections with four items each. Specifically, Test Section 1 had two lean clay test items and two heavy clay test items. Test Section 2 had four separate items: clayey sand, lean clay, silt, and heavy clay. The sections were trafficked with an F-4C single wheel with a 25,000-lb load, tire pressure of 225 psi, and contact area equal to 111 in.^{2} The failure criterion was based on rutting and permanent deformation; a section with a rut depth exceeding 3 in. was considered failed. Table 1 includes the traffic test results of Ladd's test section, which were utilized in this study. For further details, the reader may consult Ladd (1970).

Table 1. Traffic test results (Ladd 1970).

Test section	Item	Soil type	Coverages at failure	Rated CBR
1	1	CL	58	29
	2	CL	1,000*	58**
	3	CH	82	23
	4	CH	6	15
2	1	SC	26*	36**
	2	CL	26	22
	3	ML	20	18
	4	CH	4	16

Note.

* Did not fail; traffic was discontinued after 1,000 coverages on Item 2, Test Section 1, and after 26 coverages on Item 1, Test Section 2 (Ladd 1970).

** Rated CBR exceeded the value shown (Ladd 1970).

The data from Hammitt (1970) were obtained from a full-scale testing research project that had the objective of determining thickness requirements for landing-mat-surfaced, membrane-surfaced, and aggregate-surfaced airfields. The tests included three aggregate-surfaced test sections. Test Section 1 had four lanes with four items each; Test Section 2 had three lanes; and Test Section 3 had three lanes containing five items each. Table 2 contains section material characteristics, wheel load and tire pressure of the applied traffic, and a summary of the test results (Hammitt 1970). The failure criteria applied in this project were based on (1) permanent deformation (rutting) exceeding 3 in. of depth, as measured by a 10-ft straightedge or (2) elastic deformation greater than 1.5 in. In addition, the test item was considered failed when it exhibited an overall subsidence greater than 4 in.

Table 2. Traffic test results (Hammitt 1970)

Lane and loading characteristics	Test item	Cover thickness (in.)	Rated CBR		Coverages to failure
			Cover	Subgrade	
Test section 1					
Lane 1 - 15,000, single-wheel, 119 psi tire pressure, 127 in.^{2} contact area	4	6	9.0	3.2	26
	3	12	7.3	2.9	38
	2	18	9.0	4.0	88
	1	24	8.3	3.1	88
Lane 2 - 25,000, single-wheel, 101 psi tire pressure, 249 in.^{2} contact area	4	6	10.0	3.6	10
	3	12	7.0	3.9	38
	2	18	8.1	3.5	50
	1	24	9.5	3.1	116
Lane 3 - 40,000, single-wheel, 77 psi tire pressure, 520 in.^{2} contact area	4	6	10.0	3.4	6
	3	12	9.5	3.3	48
	2	18	9.0	3.7	240
	1	24	11.0	4.4	--
Lane 4 - 40,000, single-wheel, 84 psi tire pressure, 474 in.^{2} contact area	4	6	9.0	3.7	8
	3	12	8.5	2.9	46
	2	18	8.5	4.1	140
	1	24	9.7	4.3	--
Test section 2					
Lane 5 - 15,000, single-wheel, 154 psi tire pressure, 97 in.^{2} contact area	4	6	11.0	4.4	4
	3	12	10.0	3.9	18
	2	18	12.0	4.3	44
	1	24	11.0	4.0	44
Lane 6 - 40,000, single-wheel, 102 psi tire pressure, 392 in.^{2} contact area	4	6	13.0	3.5	8
	3	12	14.0	4.3	36
	2	18	10.0	4.8	100
	1	24	11.0	5.0	160
Lane 7 - 80,000, twin-twin*, 106 psi tire pressure, 520 in.^{2} contact area	4	6	10.0	3.8	3
	3	12	11.0	4.6	90
	2	18	10.0	3.5	240
	1	24	11.0	4.3	290

Lane and loading characteristics	Test item	Cover thickness (in.)	Rated CBR		Coverages to failure
			Cover	Subgrade	
Test section 3					
Lane 8 - 25,000, single-wheel, 100 psi tire pressure, 250 in.^{2} contact area	5	9	13.0	2.2	24
	4	12	14.0	2.1	48
	3	15	18.0	2.7	328
	2	18	17.0	2.9	698
	1	21	17.0	2.6	--
Lane 9 - 40,000, single-wheel, 100 psi tire pressure, 400 in.^{2} contact area	5	9	11.0	2.2	6
	4	12	12.0	2.6	6
	3	15	15.0	2.4	80
	2	18	15.0	2.9	110
	1	21	15.0	3.1	700
Lane 10 - 40,000, single-wheel, 100 psi tire pressure, 400 in.^{2} contact area	5	9	12.0	2.4	10
	4	12	13.0	2.3	20
	3	15	15.0	2.2	62
	2	18	17.0	2.9	360
	1	21	17.0	2.4	--

Note: *Spacing of these tires was 30 in. c-c, 33 in. c-c, and 30 in. c-c. This gear arrangement is similar to the nose gear arrangement proposed for the use on the C-5A aircraft.

The report by Thompson and Burns (1960) provided additional data to aid in the reformulation of the design procedure of aggregate-surfaced pavements. Thompson and Burns (1960) reported the research centered on the CBR design curves for standards mats, aggregate-surfaced pavements and membrane-surfaced pavements. The sections were trafficked with load carts with single-wheel and multiple-wheel assemblies. The loads were between 10,000 and 50,000 lb for the single-wheel assembly and between 50,000 lb and 100,000 lb for the multiple-wheel ones. Tire pressure ranged from 40 psi to 300 psi. Trafficking was applied until the sections reached failure or up to a minimum of 700 coverages if failure was not reached. As in the previous research efforts, failure criteria were based on permanent deformation and deflection under traffic. A pavement section was considered failed when permanent deformation (rutting) was between 2 in. and 4 in. and deflection ranged from 0.75 in. to 1.5 in. Table 3 contains Thompson and Burns' data of aggregate-surfaced test sections, as reported by Hammitt (1970).

Table 3. Traffic test results of Thompson and Burns (1960) from Hammitt (1970).

Loading characteristics	Thickness (in.)		Rated CBR		Coverages to failure
	Cover	Subgrade	Cover	Subgrade	
10,000, single-wheel, 110 psi tire pressure	6.0	18.0	38	5.0	120
10,000, single-wheel, 256 psi tire pressure	12.0	24.0	29	6.5	250
10,000, single-wheel, 190 psi tire pressure	6.0	18.0	31	6.5	4
	6.0	18.0	34	7.0	16
	12.0	24.0	61	6.5	618
25,000, single-wheel, 52 psi tire pressure	6.0	24.0	37	6.0	75
25,000, single-wheel, 108 psi tire pressure	6.0	24.0	39	4.5	30
25,000, single-wheel, 172 psi tire pressure	6.0	24.0	60	4.0	9
	6.0	18.0	80	11.0	100
25,000, single-wheel, 223 psi tire pressure	6.0	18.0	35	9.0	30
	12.0	18.0	73	6.0	100
50,000, single-wheel, 62 psi tire pressure	6.0	24.0	16	4.5	35
50,000, single-wheel, 104 psi tire pressure	6.0	34.0	41	4.5	15
	6.0	18.0	65	8.5	170
	12.0	24.0	105	6.0	700
50,000, single-wheel, 185 psi tire pressure	6.0	18.0	51	11.5	180
	12.0	24.0	53	4.5	15
50,000, single-wheel, 267 psi tire pressure	6.0	18.0	57	13.0	4

Data collected by Burns and McCall (1968) during full-scale tests were also utilized for determining the CBR-Beta design equation for aggregate-surfaced pavements. Burns and McCall's study had the objective of evaluating the T17 neoprene-coated nylon membrane's effectiveness in increasing the load-carrying capability of soils in road and airfield pavements. The full-scale test consisted of a 15-ft-wide and 100-ft-long section of two layers. The subgrade had a CBR value of 4, whereas the base layer had a thickness of 12 in. and a CBR equal to 10. The test section was divided into four 25-ft-long items. One of these items was constructed without a membrane and kept as a reference item. Trafficking included 100 coverages with a load cart with a 25,000-lb single wheel producing a contact pressure of 100 psi. The failure criterion was the development of a 3-in. rut measured across the test section. Table 4 summarizes the data used in developing the CBR-Beta equation for aggregate-surfaced pavements.

Table 4. Traffic test results from Burns and McCall (1968).

Test item	Base CBR	Subgrade CBR (at 12 in. of depth)	Coverages to failure
1	11	4.3	72
2	10	3.9	74
3	10	3.8	69
4	10	3.6	89

Test data collected by Ladd and Ulery (1967) were used for validating the proposed design equation for aggregate-surfaced pavements. The overall objective of Ladd and Ulery's study was to provide recommendations for designing an efficient landing gear configuration for aircraft required to operate on contingency airfields. The full-scale test also included the evaluation of mat surfaces; however, only the data referring to aggregate-surfaced pavement were considered for validation. Table 5 contains the data used for validating the CBR-Beta design equation.

Table 5. Traffic test results from Ladd and Ulery (1967)

<table>
<tr><th>Load per tire (lb) and configuration (S=single; MW=multiple wheel)</th><th>Tire pressure (psi)</th><th>CBR</th><th>Coverage at failure</th></tr>
<tr><td rowspan="6">1,000(S)</td><td rowspan="2">10</td><td>1.1</td><td>178</td></tr>
<tr><td>1.4</td><td>200</td></tr>
<tr><td>20</td><td>1.0</td><td>24</td></tr>
<tr><td>30</td><td>1.1</td><td>18</td></tr>
<tr><td>40</td><td>1.2</td><td>50</td></tr>
<tr><td>40</td><td>2.3</td><td>38</td></tr>
<tr><td rowspan="2">2,000(S)</td><td>60</td><td>2.6</td><td>50</td></tr>
<tr><td>80</td><td>2.5</td><td>44</td></tr>
<tr><td rowspan="2">2,500(S)</td><td rowspan="2">25</td><td>1.3</td><td>30</td></tr>
<tr><td>2.1</td><td>80</td></tr>
<tr><td>19,000(S)</td><td>100</td><td>8.4</td><td>32</td></tr>
</table>

Load per tire (lb) and configuration (S=single; MW=multiple wheel)	Tire pressure (psi)	CBR	Coverage at failure
21,000(S)	100	4.2	3
		6.3	26
		7.5	40
25,000(S)	25	3.9	200*
	40	4.7	150
	60	4.6	30
	80	5.0	20
	100	3.9	3
		7.8	200
		9.2	70
	250	10.0	10
		14.0	60
	100	7.8	100
	250	10.0	1
		14.0	6
35,000(S)	50	12.0	600*
		4.7	300
	100	6.7	10
		9.5	60
		11.0	50
		6.7	4
		9.2	16
60,000(S)	100	12.0	112
		16.0	130
35,000(MW)	50	4.5	200
		4.8	100
		4.7	200
	110	10.0	20
	100	9.2	12
		9.0	36
		10.0	50
		9.8	62
		9.3	100
		10.0	30
		11.0	72

Load per tire (lb) and configuration (S=single; MW=multiple wheel)	Tire pressure (psi)	CBR	Coverage at failure
		9.8	20
		9.8	24
52,000(MW)	200	10.0	2
		18.0	130
		10.0	2
		27.0	300*
60,000(MW)	100	9.0	44
21,000(MW)	55	2.3	1.3
		4.4	25
		8.1	*59***
		2.5	1.3
		4.7	49
		7.0	400
	100	3.8	2.4
		6.1	28
		10.0	730
22,750(MW)	100	9.0	455

Note: *No failure developed. **This data point was excluded from the validation since it was considered an outlier based on Ladd and Ulery's report.

2.3 The CBR-Beta equation for aggregate-surfaced pavements

The CBR-Beta equation for asphalt-surfaced pavements is

$$\log(\boldsymbol{\beta}) = \frac{1.5441 + 0.073\log(\boldsymbol{cov})}{1 + 0.2354\log(\boldsymbol{cov})} \tag{8}$$

where:

cov = number of coverages applied to the pavement
β = stress ratio as defined in Equation 9. Also

$$\beta = \frac{\pi\sigma}{CBR} \tag{9}$$

where:

σ = stress at the top of the subgrade or the aggregate layer, psi

In analogy to the CBR-Beta equation for the design of flexible pavements, the design equation for aggregate-surfaced pavements has a similar format, as shown in Equation 10.

$$\log(\beta) = \frac{a + b\log(\text{cov})}{1 + c\log(\text{cov})} \tag{10}$$

where:

β = stress ratio as defined in Equation 9
a, b, c = curve parameters

The values of a, b, and c were determined by forcing the failure curve to pass through two selected points that represented pavement failure occurring at a lower value of passes or Beta values, indicated in (Figure 3) as points A and B, which have coordinates (4, 44.18) and (100, 23.14), respectively. These two points were taken as benchmarks, or boundary conditions, for the envelope curve enclosing most of the test failure points. Those points below the curve included five points from the full-scale test by Thompson and Burns (1960) and two from the work by Ladd (1970). Table 6 summarizes these excluded values. These points were not considered in the development of the criteria curve of Equation 10 because in some cases the points represented a section partially failed or were considered as outliers within the set of data collected during each respective experiment. Equation 10 represents the CBR-Beta criterion derived for the design of aggregate-surfaced pavements and is illustrated by the continuous line in Figure 3.

$$log(\beta) = \frac{1.8451 + 0.1914\log(\text{cov})}{1 + 0.3193\log(\text{cov})} \tag{11}$$

The pavement performance curve modeled on the full-scale tests' data was adjusted with consideration to the contextual information of each point. The curve does not represent the best fit from the mathematical and statistical standpoints.

Figure 3. CBR-Beta equation for aggregate-surfaced pavements.

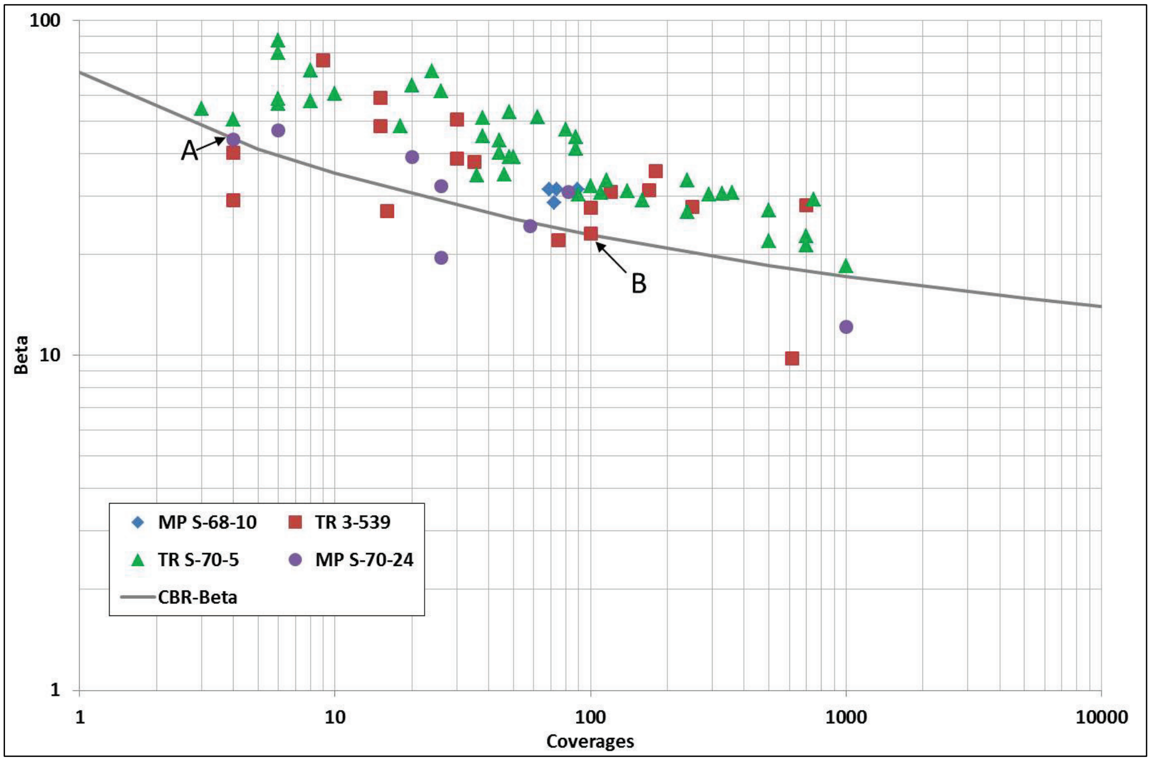


Table 6. Points excluded from the CBR-Beta criteria envelope curve.

Reference report	Coverages	Beta
TR 3-539	4	29.14
	16	27.06
	618	9.78
	75	22.04
	4	40.21
MP S-70-24	1,000	12.19
	26	19.63

As previously mentioned, the data produced by Ladd and Ulery (1967) were used for validation of the proposed design equation for aggregate-surfaced pavements. Figure 4 shows the newly developed CBR-Beta criteria superimposed over the test data points from Ladd and Ulery (1967). Four points (Table 7) ended up in the failed area and below the CBR-Beta criteria curve. This plot shows that the failure curve is conservative and that only four points fall below the curve. In general, the proposed failure curve follows the general trend exposed by the test data points.

Figure 4. CBR-Beta equation with superimposed validation points.

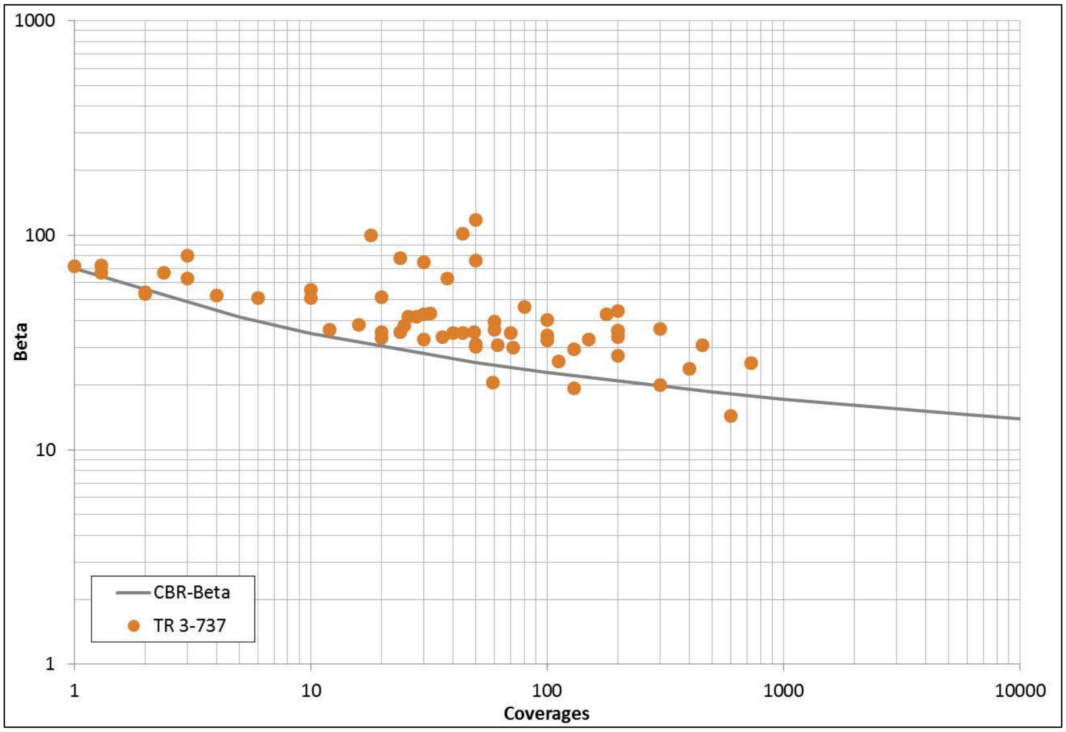


Table 7. Points excluded from the CBR-Beta criteria envelope curve after validation.

Reference report	Coverages	Beta
TR 3-737	600	14.40
	130	19.44
	2	53.09
	59	20.56

3 Comparison of the Design Procedures

After defining the new CBR-Beta design procedure for aggregate-surfaced pavements, the new procedure was compared to the existing CBR-Alpha approach. The comparison allowed evaluating the impact of the Fröhlich's stress distribution model and the change of the equivalent single-wheel concept with regards to the load application. In fact, as in the CBR-Beta design procedure for flexible pavements; each wheel in the aircraft assembly contributes to stress distribution within the underlying medium.

The first comparison was conducted on the basis of the number of passes of a specific aircraft that was allowed to use an aggregate-surfaced pavement with given CBR and thickness of the aggregate cover material and subgrade CBR. Table 8 summarizes the aircraft type and weight used for the comparisons. Table 9 includes the different combinations of aggregate-surfaced pavement with regards to cover thickness and CBR and subgrade CBR.

Table 8. Type of aircraft used for comparison.

Type of aircraft	Gross weight, lb
C-130	170,000
C-17	486,000

Table 9. Aggregate-surfaced pavement combinations.

	Combination 1	Combination 2	Combination 3
Cover CBR (variable thickness)	10	15	-- (zero thickness)
Subgrade CBR	3	3	variable

The two procedures were also compared in the determination of the required cover thickness and CBR needed to support a specific traffic level for a given subgrade CBR. The traffic included the C-130 and C-17 aircraft with the number of passes between 1 and 1,000 on a traffic type area A. The assumed subgrade CBR values were 3, 5, and 10.

Tables 10 and 11 summarize thickness-cover requirements and allowable number of passes computed through the CBR-Alpha and CBR-Beta procedures for the C-17 and C-130 aircraft traffic, for given subgrade CBR equal to 3 and cover material CBR equal to 10 and 15. Table 12 includes the number of passes to failure for the C-17 and C-130 aircraft that a surface with a given CBR is able to support. In this case, the thickness of the cover material is equal to zero.

Table 10. C-17 allowable passes and thickness-cover requirement.

C-17	Subgrade CBR = 3 cover CBR = 10		Subgrade CBR = 3 cover CBR = 15	
Cover thickness, in.	Allowable passes w/CBR-Alpha	Allowable passes w/CBR-Beta	Allowable passes w/CBR-Alpha	Allowable passes w/CBR-Beta
0	0	0.31	0	0.31
1	0.43	0.32	0.43	0.32
2	0.64	0.34	0.64	0.34
3	0.95	0.37	0.95	0.38
4	1.41	0.45	1.41	0.45
5	2.07	0.63	2.07	0.63
6	3.02	0.80	3.02	0.80
7	4.37	1.04	4.37	1.00
8	6.26	1.37	6.26	1.40
9	9*	1.86	8.92	1.86
10	9	2.55	12	2.60
11	9	3.56	17	3.60
12	9	5.07	24	5.10
13	9	5.61	33	7.30
14	9	6	45	11
15	9	6	61	16
16	9	7	81	24
17	9	7	97 *	32
18	9	8	97	36
19	9	8	97	41
20	9	9	97	47

Note. *From this point on, failure occurs in the surface layer.

Table 11. C-130 allowable passes and thickness-cover requirement.

C-130	Subgrade CBR = 3 cover CBR = 10		Subgrade CBR = 3 cover CBR = 15	
Cover thickness, in.	Allowable passes w/CBR-Alpha	Allowable passes w/CBR-Beta	Allowable passes w/CBR-Alpha	Allowable passes w/CBR-Beta
0	0	0.71	0	0.71
1	0.75	0.72	0.75	0.72
2	1.15	0.76	1.15	0.76
3	1.76	0.83	1.75	0.83
4	2.70	0.95	2.70	0.85
5	4.10	1.17	4.10	1.20
6	6.30	1.64	6.30	1.65
7	9.56	2.10	9.56	2.10
8	14.50	2.70	14.50	2.70
9	22	3.60	22	3.56
10	33	4.80	33.	4.80
11	*40**	7	50	6.60
12	40	9	74	9.24
13	40	13	111	13
14	40	18	165	19
15	40	20	245	29
16	40	22	365	44
17	40	24	*461**	68
18	40	27	461	108
19	40	30	461	154
20	40	34	461	156

Note. *From this point on, failure occurs in the surface layer.

Table 12. C-17 and C-130 allowable passes for variable CBR subgrade.

At zero thickness	C-17		C-130	
Subgrade CBR	Passes Alpha	Passes Beta	Passes Alpha	Passes Beta
1	0	0	0	0.16
2	0	0.17	0	0.38
3	0	0.31	0	0.71
4	0	0.51	1.17	1.22
5	0.13	0.79	0.63	2.03
6	0.4	1.2	1.9	3.24
7	1	1.77	4.76	5.1
8	2.2	2.6	10.6	7.84

At zero thickness	C-17		C-130	
Subgrade CBR	Passes Alpha	Passes Beta	Passes Alpha	Passes Beta
9	4.5	3.7	21	12
10	8.6	5.34	40	18
12	26	11	121	41
13	41	15	195	62
14	64	21	305	94
15	97	30	461	142
16	144	42	679	215
17	207	60	976	327
18	291	84	1376	498
19	403	119	1903	764
20	548	168	2589	1179
22	970	340	4587	2861
25	2090	1005	9876	11498

Figure 5 offers a visual comparison between the allowable number of passes for the C-130 and the C-17 supported by an aggregate-surfaced pavement where the subgrade CBR is equal to 3 and the CBR of the cover layer is equal to 10. Figure 6 also illustrates similar comparisons between allowable passes for a subgrade CBR equal to 3 and cover material CBR equal to 15. Figure 7 provides a graphic representation for direct comparison of the data in Table 12.

In Figures 5 and 6, the difference between the two design procedures is readily apparent. The curves representing the CBR-Alpha design procedure after a specific number of passes become horizontal, indicating that failure occurs at the cover layer and not at the subgrade level. For both types of aircraft, the CBR-Beta design procedure is more conservative, allowing a lower number of passes than the CBR-Alpha procedure for the same aggregate-surfaced pavement structure (same cover CBR and thickness). For example, an existing aggregate-surfaced pavement structure characterized by an 18-in. cover with CBR of 15 and placed over a subgrade with CBR of 3 allows 32 passes of a C-17 if evaluated with the CBR-Beta procedure, whereas the C-17 is allowed 98 passes if evaluated with the CBR-Alpha procedure.

Figure 5. C-17 and C-130 allowable passes on aggregate-surfaced pavement with subgrade CBR equal to 3 and cover CBR equal to 10.

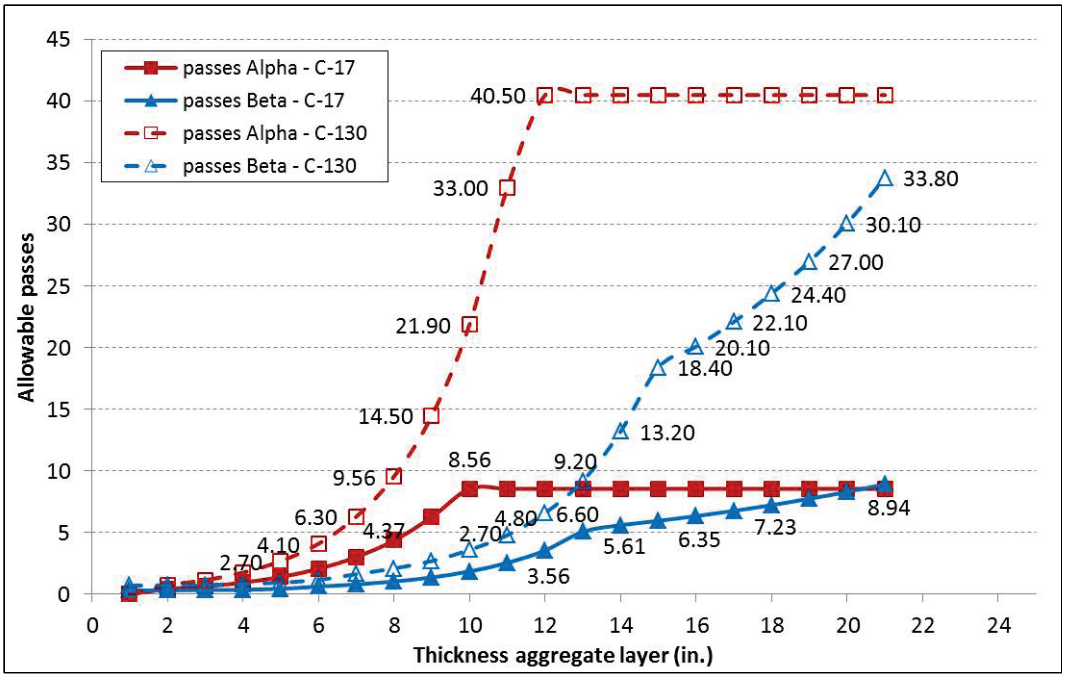


Figure 6. C-17 and C-130 allowable passes on aggregate-surfaced pavement with subgrade CBR equal to 3 and cover CBR equal to 15.

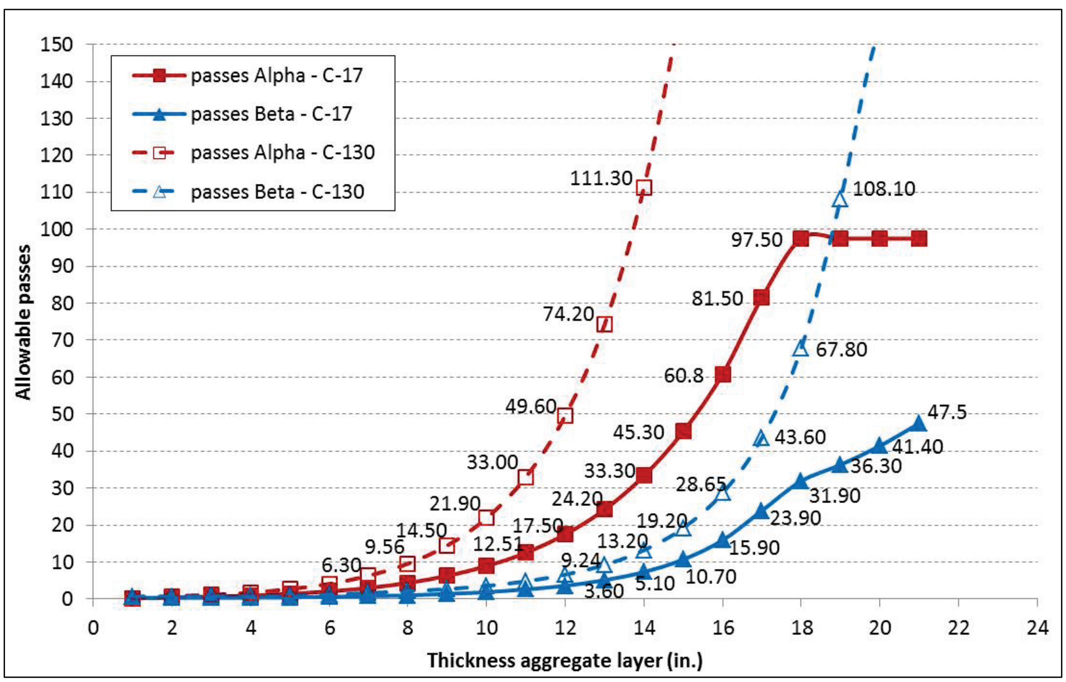
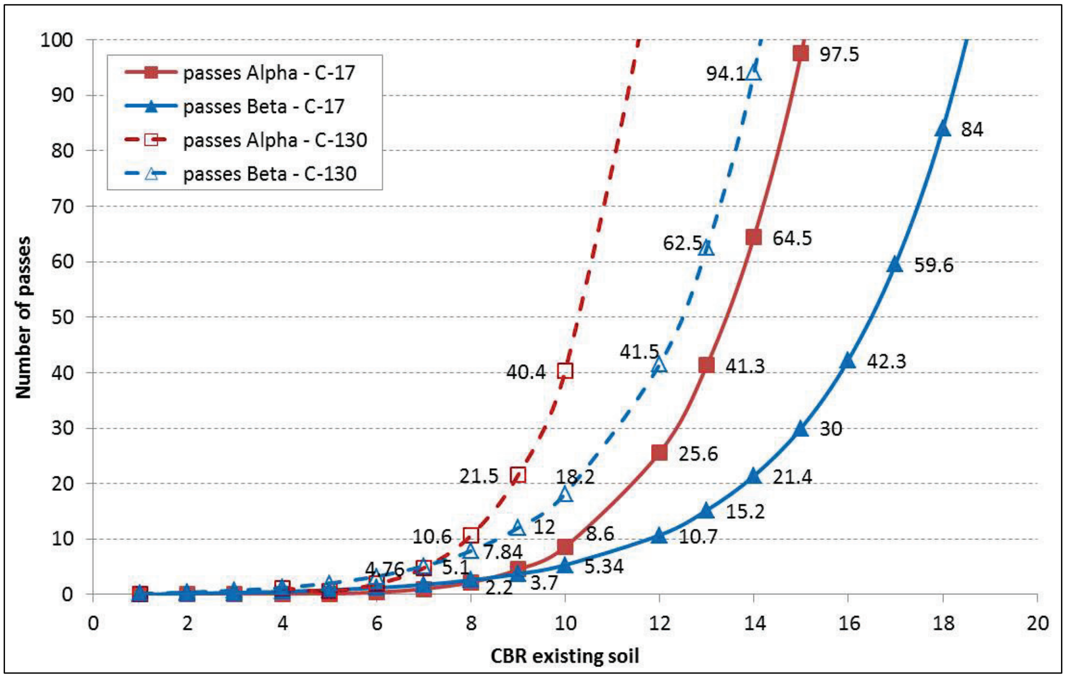


Figure 7. C-17 and C-130 allowable passes on variable CBR soil.



The conservative aspect of the CBR-Beta procedure appears in all the other structure combinations evaluated within this study. This aspect is further emphasized by the charts of Figures 8 to 11. Figures 8 to 11 contain the data in Tables 10 and 11 with the addition of the case of the subgrade CBR equal to 5. These charts depict the cover thickness as a function of the cover CBR for a given subgrade CBR value. The data labels on the curve refer to aircraft allowable number of passes that the pavement system can support. For example, over a subgrade with CBR equal to 5, 10 passes of a C-130 require at least 8.6 in. of cover material with CBR of 8.2, if determined by the CBR-Beta procedure, whereas if designed with the CBR-Alpha procedure, the same conditions require 5.35 in. of cover material with a slightly lower CBR of 7.92. Figure 10 provides direct comparison of the two procedures. On a subgrade with CBR equal to 5, a cover of 16.5 in. with CBR equal to 15 provides support to 60.7 passes of a C-17, based on the CBR-Beta procedure; the number of passes supported by the same structure if computed though the CBR-Alpha procedure is 97.5.

Figure 8. CBR of the cover material as a function of the cover thickness and C-130 number of passes, subgrade CBR equal to 5.

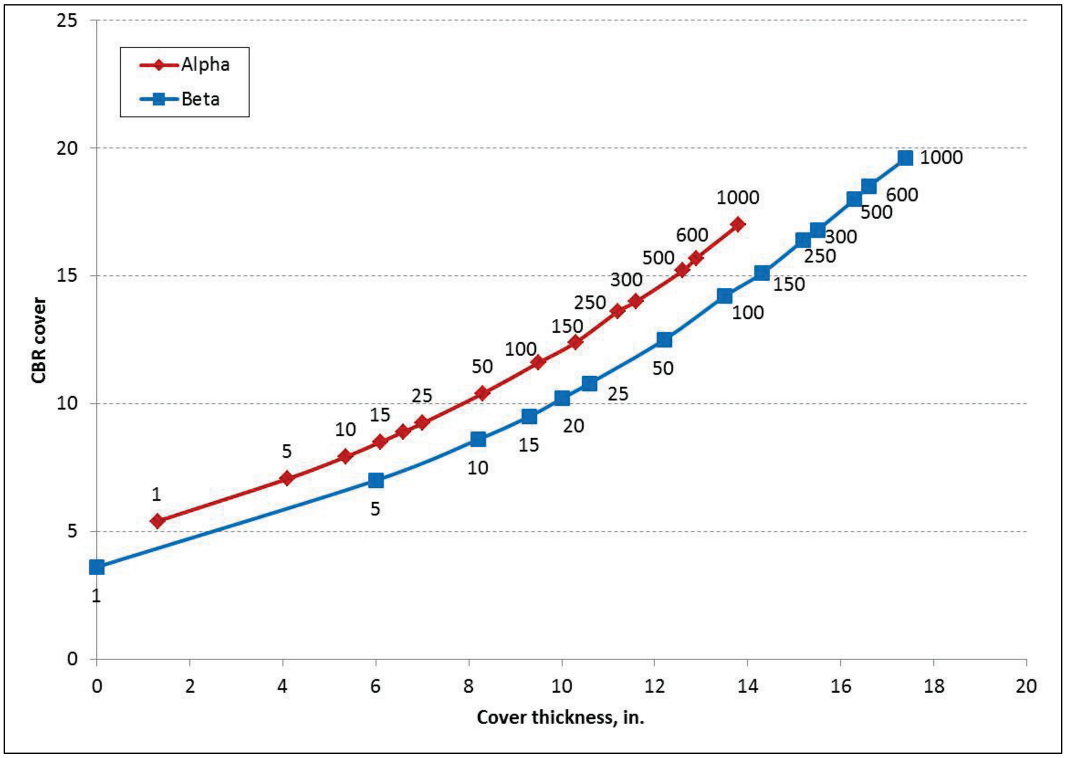


Figure 9. CBR of the cover material as a function of the cover thickness and C-130 number of passes, subgrade CBR equal to 3.

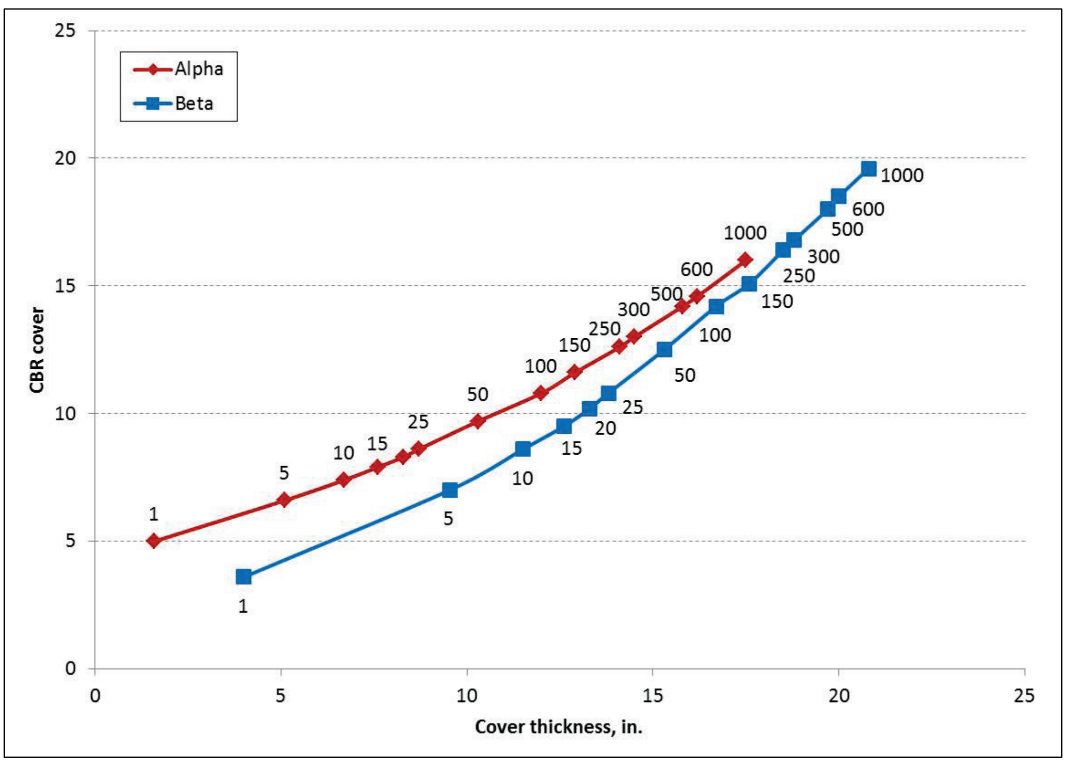


Figure 10. CBR of the cover material as a function of the cover thickness and C-17 number of passes, subgrade CBR equal to 5.

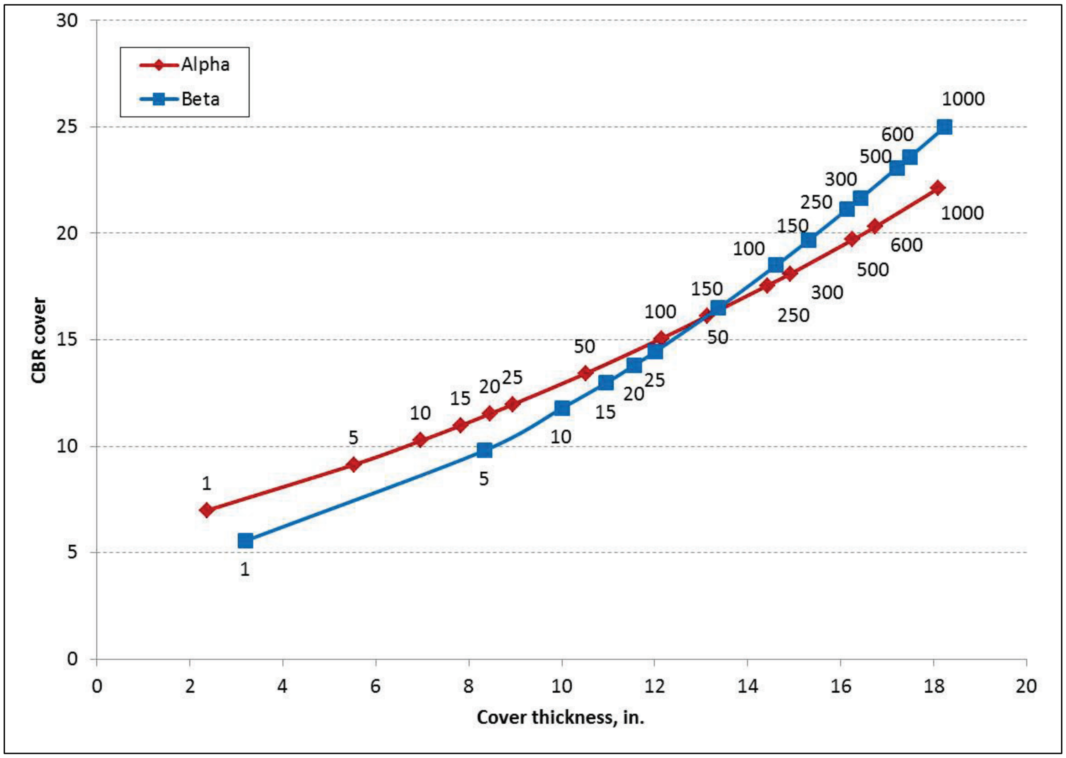
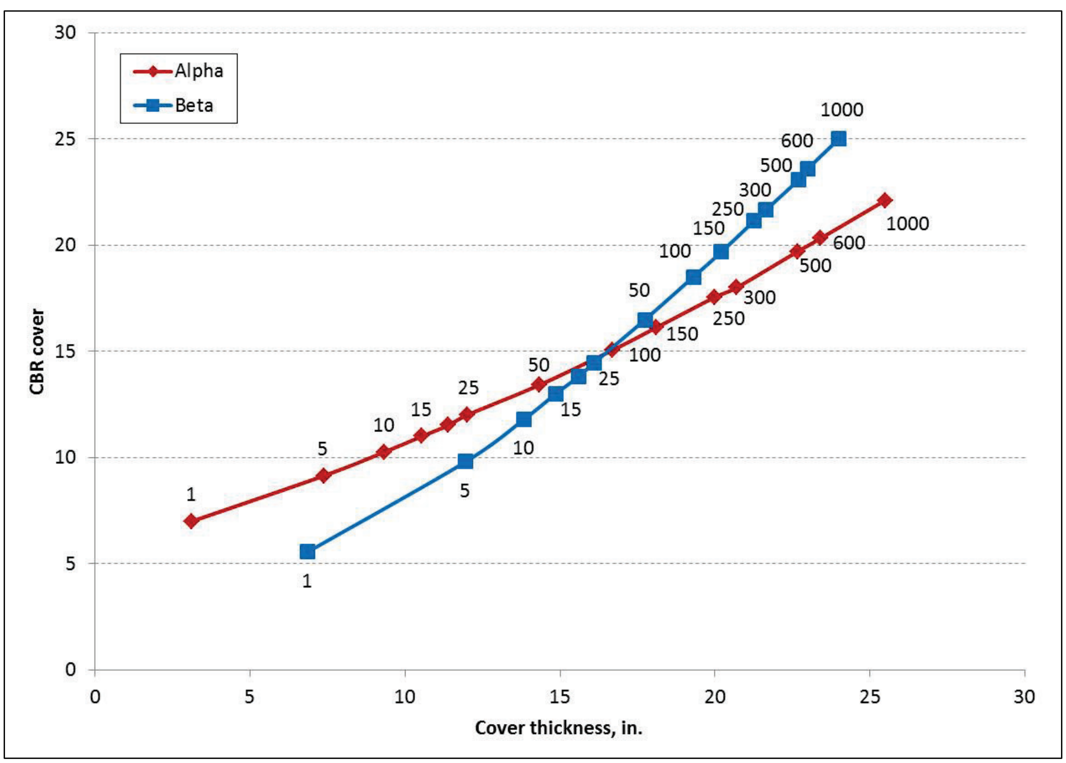


Figure 11. CBR of the cover material as a function of the cover thickness and C-17 number of passes, subgrade CBR equal to 3.



The differences between the two procedures are primarily caused by the difference in the modeling of the physical problem with regards to the stress distribution and the ESWL concept applied in the CBR-Alpha design equation. Moreover, the CBR-Alpha procedure is based on the assumption of constant contact area with variable tire pressure, whereas the CBR-Beta procedure assumes variable contact area with constant tire pressure up to certain limits dictated by the realistic amount of tire deformation. Because of the assumptions embedded in the CBR-Alpha procedure, the extrapolation and the generalization of this design procedure to other aircraft types and pavement structures that were not included within the full-scale tests are questionable, may provide approximate results, and are affected by large variability originally enclosed in the same assumptions. Therefore, the CBR-Alpha and the CBR-Beta procedures cannot be effectively compared, and such comparison depends on the pavement conditions in terms of subgrade CBR, thickness of cover, and type of loading used.

4 Summary and Recommendations

The original curves for designing aggregate-surfaced pavements were derived from those empirically based on the California method, which utilized the Boussinesq's theory of stress distribution in a homogenous half-space. The reformulation of the CBR design procedure for asphalt-surfaced pavement using the Fröhlich's theory of stress distribution in the half-space provided a new opportunity to redefine the design procedure of aggregate-surfaced pavements.

4.1 Summary

The reformulation of the CBR-Alpha design procedure for aggregate-surfaced pavements utilized past test data derived from full-scale testing conducted in the 1970s at the ERDC in Vicksburg. The analyses included in this report are summarized in the following paragraphs:

1. The design procedure was reformulated by applying the Fröhlich's theory of stress distribution, and provided the following Equation (11bis).

$$\log(\beta) = \frac{1.8451 + 0.1914\log(\text{cov})}{1 + 0.3193\log(\text{cov})} \qquad (11\text{ bis})$$

2. Test data collected by Ladd and Ulery (1967) were used for validating the proposed design equation for aggregate-surfaced pavements. The validation produced satisfactory results.
3. The CBR-Alpha and the CBR-Beta procedures were compared to each other utilizing a C-17 (486,000 lb) and a C-130 (175,000 lb). For both aircraft, the CBR-Beta procedure computed more conservative results than the CBR-Alpha procedure. In fact, greater cover thickness and CBR were required for supporting the same number of aircraft passes. Similarly, the CBR-Beta design procedure computed a lower number of allowable passes than the CBR-Alpha procedure for the same pavement structure in terms of cover thickness, cover CBR, and subgrade CBR.

4.2 Recommendations

Based on the conclusions from the data analysis, it is recommended to adopt the CBR-Beta procedure for the design and evaluation of aggregate-surfaced pavements. In addition, replacement of the CBR-Alpha procedure with the newly defined and validated CBR-Beta procedure is recommended with the objective of maintaining consistency between the design procedures of a layered pavement system. It is also recommended that the performance criteria curve be reviewed by the DoD criteria committee and adjusted if necessary.

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14. ABSTRACT

During contingency operations, aircraft are required to land, taxi, and take off on unpaved surfaces. Limited time available to establish airfield operations may not allow for the construction of paved surfaces. The original flexible pavement design procedure of paved surfaces, which is based on the California Bearing Ratio (CBR) and the α-factor (Alpha-factor), was also extended and applied to the design and evaluation of aggregate-surfaced pavements. With the reformulation of the CBR-Alpha for the design of flexible pavements, efforts were also directed in defining a new equation for the design of aggregate-surfaced airfields. This report presents the development of a new CBR-Beta procedure for the design and evaluation of aggregate-surfaced airfields. Data from previous studies conducted on aggregate-surfaced, full-scale test sections were used for this purpose. The new performance curve proposed in this report for aggregate-surfaced airfields has the same equation format as that proposed and accepted for flexible pavements.

15. SUBJECT TERMS

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